

NASA Technical Memorandum

89031

NASA-TM-89031 19860023039

Analysis of the Effects of Firing Orbiter Primary Reaction Control System Jets with an Attached Truss Structure

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August 1986

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1.0 FOREWORD

The possibility of having to fire the orbiter Primary Reaction Control System (PRCS) jets during construction of the space station would require a critical decision - whether or not to jettison a partially assembled structure if there is danger of structural failure. This scenario could arise in the event of vernier jet failure during construction of the structure, since vernier failure would require the use of the PRCS jets for attitude control. To understand the consequences of such a decision, it is necessary to determine the dynamic response of the orbiter and an attached structure during PRCS firing. In particular, determination of an envelope of PRCS operation which can be tolerated at any given stage of construction is highly desirable.

The Structural Analysis Verification Experiment (SAVE) (see reference 1) is a proposed flight experiment designed to evaluate and demonstrate the validity of the design procedures, assembly processes, and analytical tools to be used for the development of the space station. Thus, the SAVE structure would be as representative as possible of both the hardware and assembly procedures of the space station. Clearly, the technical and programmatic issues raised during the design and implementation of SAVE would have direct analogies during the evolution of the space station.

The study described herein makes a simple evaluation of the effects of firing the orbiter PRCS jets while the SAVE structure is attached to the payload bay. While the proposed SAVE structure is different in detail from any of the truss sections which will likely make up the space station, it is nonetheless representative of the size and dynamic characteristics of a structure which could reasonably be built during a single shuttle mission. Therefore, the results of this study should provide a good basis for further analysis as the actual design of the space station proceeds.

2.0 SUMMARY

This study shows that it is possible to define some simple scenarios by which to adjust the attitude of the orbiter using PRCS jets without failure of the SAVE structure. However, it is clear that the magnitude and type of orbiter motion that can be tolerated is limited. Thus, a more detailed analysis is necessary to precisely define the operational constraints on PRCS firing that will be required for safe assembly and testing of the SAVE structure. Similar operational constraints will be necessary for the first several steps of the space station assembly process, and further analysis should attempt to quantify those limits as well.

3.0 INTRODUCTION

This study considers the effect that firing the orbiter PRCs jets has on the baseline SAVE structure; the aim being to determine the approximate limits of orbiter motion that can be tolerated by the structure without failure of a truss member.

The baseline SAVE structure which was used for this study is shown on figure 1. The following list details the important features of the baseline configuration.

- a. A main truss section of 16 bays of 5 meter orthogonal tetrahedral truss built in the orbiter z-axis.
- b. 2 truss bays on each side of the main section which form a 4 bay "T" section.
- c. The "T" section is oriented perpendicular to the orbiter payload bay and there is a mass of 453.4 kg on each tip.
- d. A total of 2286 kg of non-load carrying utility trays distributed along both sides of the eight bays nearest the orbiter.
- e. The truss members are graphite epoxy tubes with an outside diameter of 0.0508 m and a wall thickness of 1.5×10^{-3} m. The tubes have a Young's modulus of 2.7579×10^{11} nt/m², a cross sectional area of 2.359×10^{-4} m², and a density of 1605.4 kg/m³.

The following sections give the details of the finite element model that was used for this study, and the corresponding results.

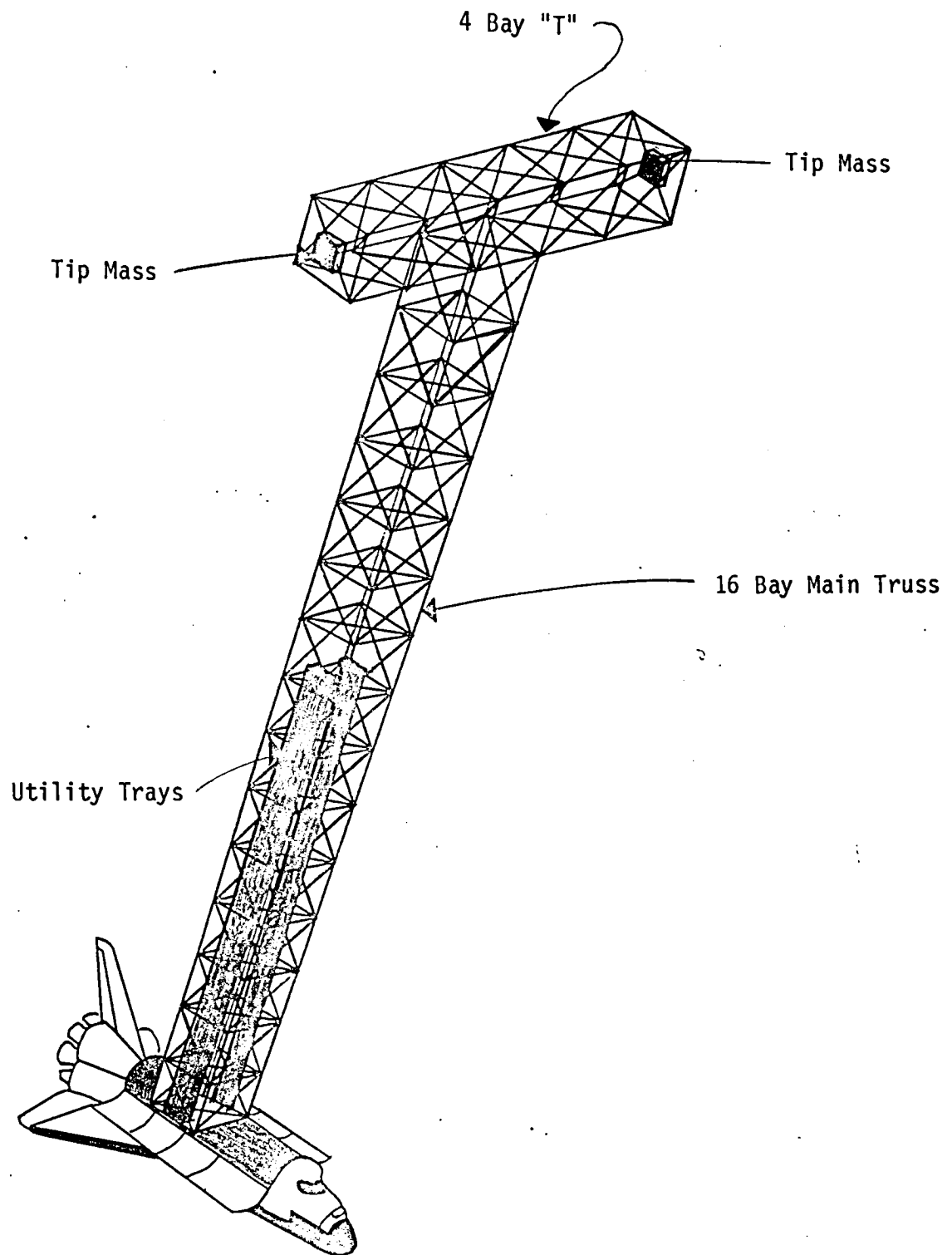


Figure 1 - Baseline SAVE Configuration.

4.0 MODEL DESCRIPTION

The MSC/NASTRAN finite element model which was used for this study consists of the orbiter attached to the SAVE structure with all the features listed in the previous section. The individual truss members were modeled with ROD elements (axial stiffness only) with an assumed modal damping ratio of 1/2 %. The joints which connected the truss members were represented as 5.2 kg point masses.

The orbiter was modeled as a rigid body with all 6 vernier and 38 primary Reaction Control System jets modeled at their correct positions, with their appropriate force magnitudes and directions. Figure 2 (taken from reference 2) shows the identification code and location and direction of each jet.

The rigid body mass properties of the orbiter, the SAVE structure, and the SAVE structure attached to the orbiter are shown in table 1.

The orbiter and the SAVE structure were connected by linear springs at the four points at the base of the main truss section. Two of the points are designated as "forward" connection points and two as "aft", referring to their position in the payload bay. Each connection point had three springs; one along the x-axis, one along the y-axis, and one along the z-axis. Figure 3 shows the forward and aft connection points with the corresponding axis directions.

The springs followed the usual linear spring relation :

$$F = Kx$$

where the stiffness value (K) was varied to represent the approximate stiffness of the connection in each direction. Table 2 shows the stiffness values that were used for the connections in this study. These stiffness values were based on the stiffness of the orbiter payload bay at the locations where the SAVE structure is likely to be attached.

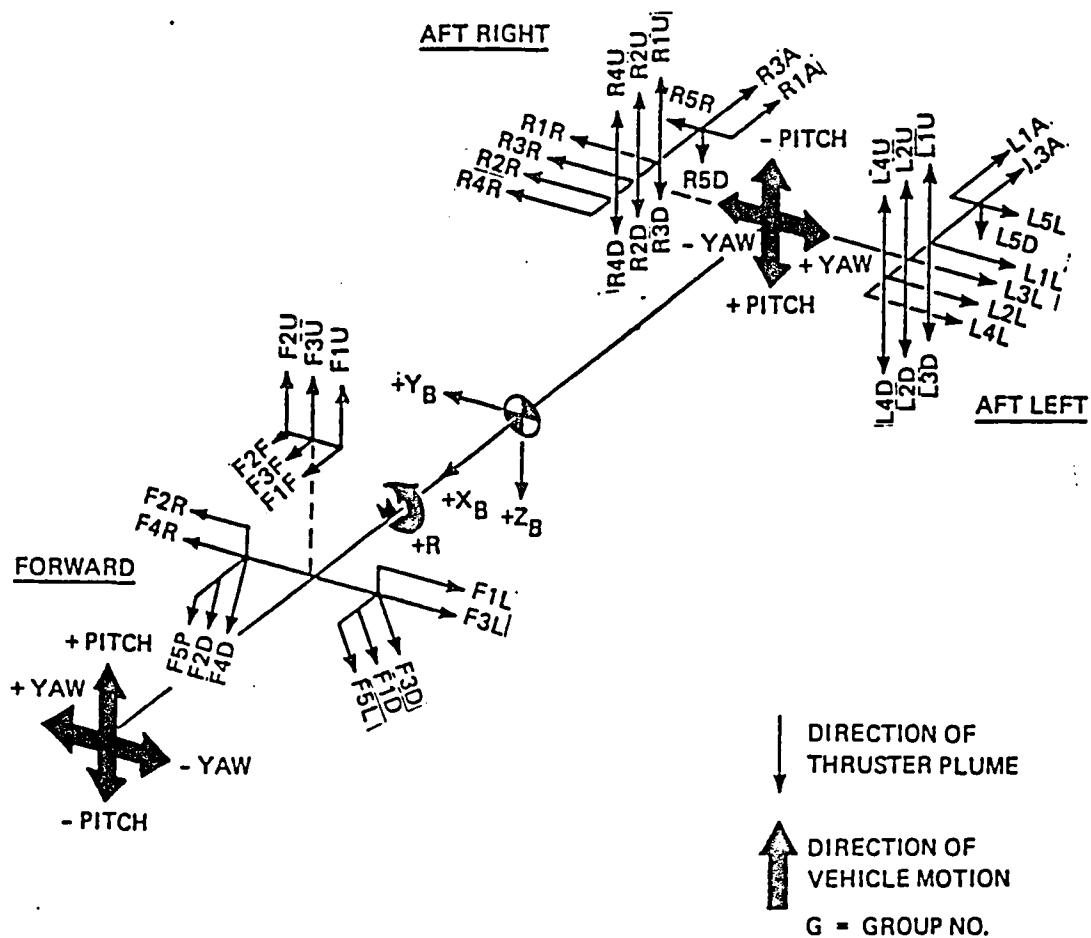
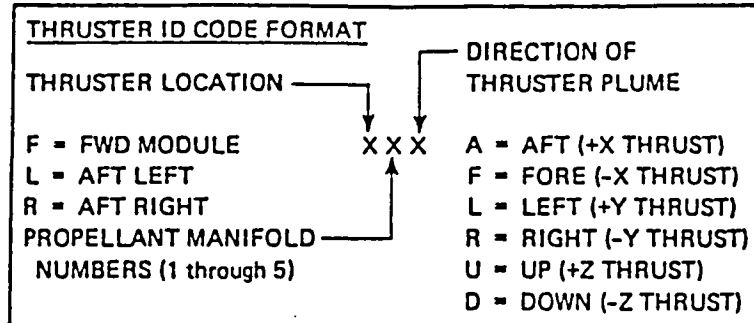


Figure 2 - RCS Jet Locations and Plume Directions.

TABLE 1 - Mass Properties of Orbiter and SAVE

| | Orbiter | SAVE | Orbiter with SAVE attached |
|----------------------------|---------------------------|---------------------------|-------------------------------|
| Mass (kg) | $1.06757 \times 10^{**5}$ | $4.26156 \times 10^{**3}$ | $1.11019 \times 10^{**5}$ |
| Ixx (kg-m**2) [roll] | $1.3598 \times 10^{**6}$ | $3.46613 \times 10^{**6}$ | $1.20837 \times 10^{**7}$ |
| Iyy (kg-m**2) [pitch] | $1.0167 \times 10^{**7}$ | $3.30281 \times 10^{**6}$ | $2.07273 \times 10^{**7}$ |
| Izz (kg-m**2) [yaw] | $1.0641 \times 10^{**7}$ | $1.90503 \times 10^{**5}$ | $1.08338 \times 10^{**7}$ |

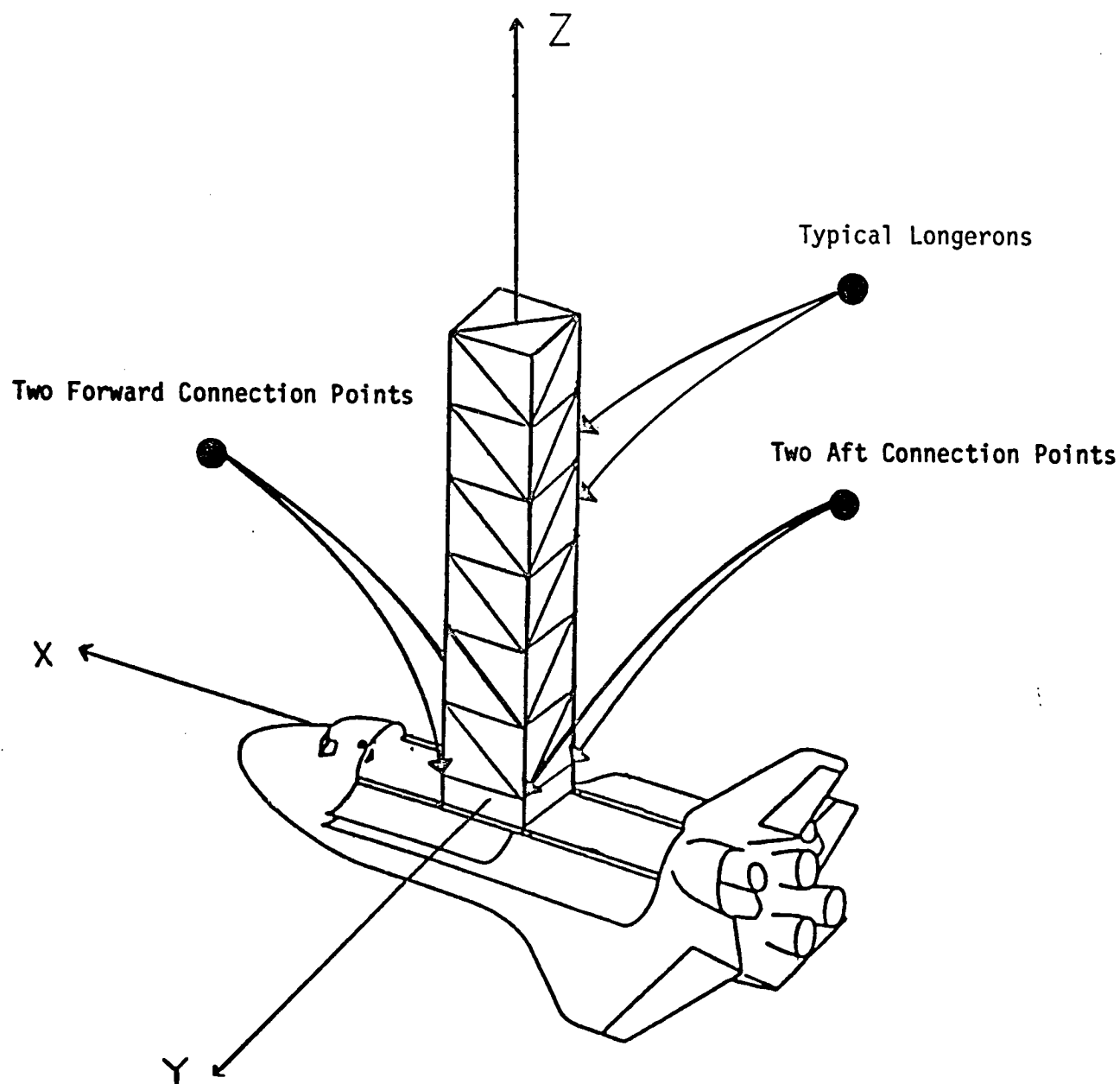


Figure 3.- Forward and Aft Connection Points.

TABLE 2 - Connection Fixture Stiffnesses

| Connection Points | Connection Stiffness (10**7 nt/m) | | |
|-------------------|-----------------------------------|-----|------|
| | X | Y | Z |
| Forward | 3.8 | 0.2 | 1.25 |
| Aft | 4.1 | 0.4 | 3.8 |

5.0 STUDY APPROACH

For a given shuttle maneuver there are five parameters which must be determined.

1. The set of RCS jets which are fired.
2. The number of pulses that each jet fires.
3. The length of each pulse.
4. The frequency of each pulse.
5. Whether each jet is fired individually (with its own pulse length, and frequency) or all jets are fired according to the same timing pattern.

Ideally, a study of this type would parametrically vary each of the above parameters and determine a data point for each permutation. Clearly, the scope of this study precludes that magnitude of analysis, due to the excessive number of computer runs that would be required. However, there are some simple assumptions that can be made which reduce the size of the problem but still produce some meaningful, though incomplete, results.

The assumptions made for this study are as follows :

1. For a given maneuver, all jets were fired according to the same timing pattern.
2. A subset of the complete problem was investigated by assuming that as one parameter was varied, all other parameters remained constant. For example, the set of PRCS jets which were fired was varied while the pulse length, the number of pulses, and the frequency of pulses were held constant. Thus, a curve was generated which shows the relation between an output parameter (such as load in a member) versus the torque created by each set of jets. Similar curves were generated for variations of the other parameters.
3. Only a positive pitch maneuver was considered. It was found from previous study that both the pitch and roll maneuvers potentially produce member loads which exceed the allowed buckling load. However, since the PRCS jets do not produce a pure roll moment, it was decided to concentrate on motion in the pitch plane only. Furthermore, since the first natural mode of the SAVE structure is bending in the pitch plane, it was clear that impulsive forces such as those that the PRCS jets produce would create greater reactions when a pitch maneuver was executed.
4. To produce the pitch motion, a set of twelve jets was selected which generated a fairly pure pitch moment.

| | | | | |
|-----|-----|-----|-----|------------------|
| F1D | L1U | R1U | F5R | |
| F2D | L2U | R2U | F5L | (see figure 2) |
| F3D | L4U | R4U | | |
| F4D | | | | |

These jets produce a total pitch torque of $4.74338 \times 10^{*5}$ nt-m (see reference 3). While these jets may or may not be used in a realistic maneuver, their use in this context was adequate for the purpose of this study.

The remaining sections present the details of the study procedure and the results obtained.

6.0 RESULTS

The results presented take the form of three curves. Each curve represents the maximum compressive load in a longeron at the base of the truss (see figure 3) for one of the following three positive pitch scenarios:

1. The pulse length varied from 80 ms to 150 ms for a single pulse of the 12 jets listed above. The result is a curve of member load versus pulse length.
2. One 80 ms pulse of several sets of jets, each of which was a subset of the set listed above. The result is a curve of member load versus the torque produced by each set of jets.
3. Five 80 ms pulses of the same jets as above, fired at various frequencies. The result is a curve of member load versus pulse frequency.

6.1 Longerons Load -vs- Pulse Length

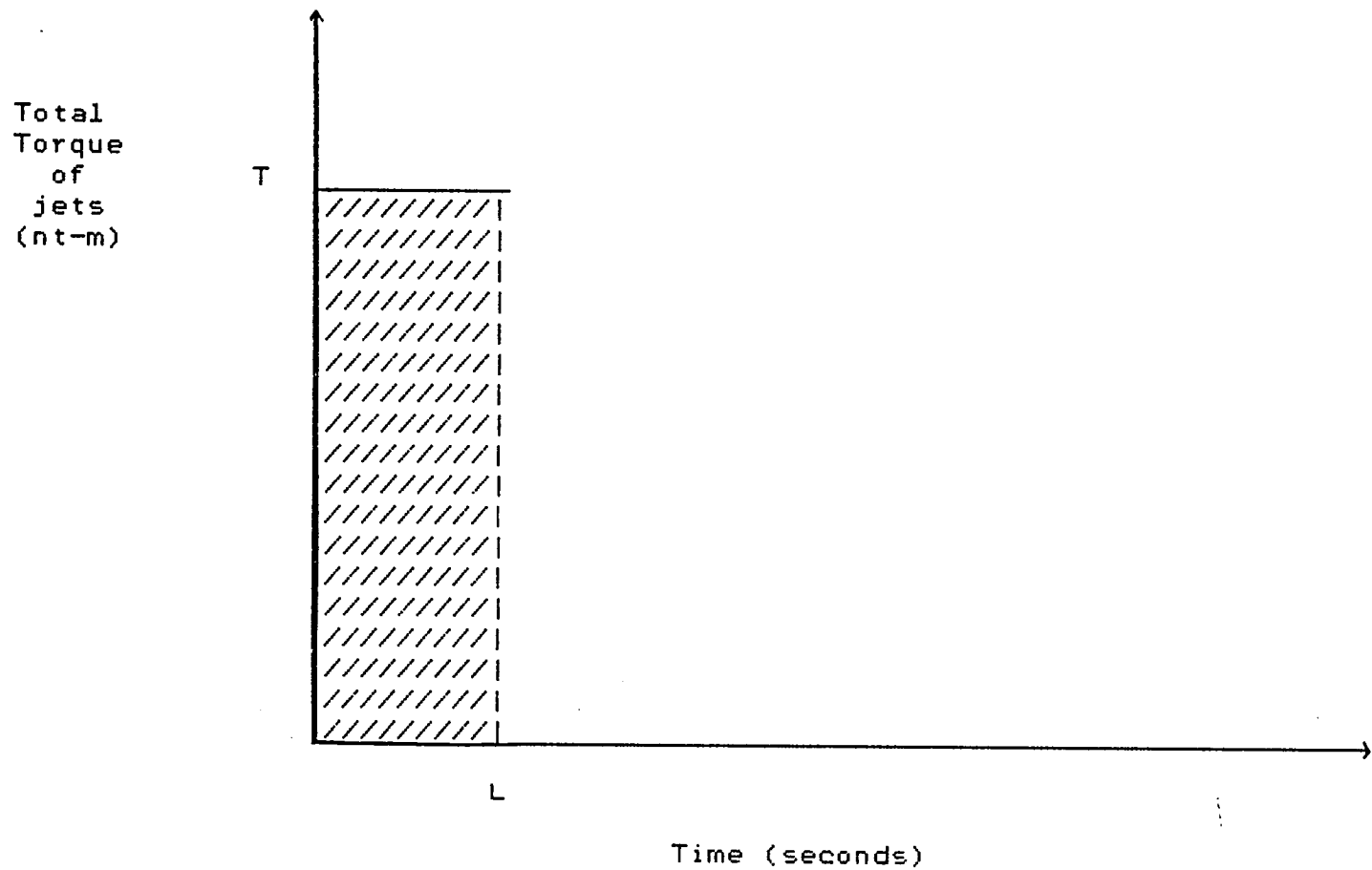
A series of cases were evaluated where the PROS jets listed in section 5.0 were fired in a single pulse. In each case the length of the pulse was changed. Figure 4 shows the forcing function that was used, where L is the length of the pulse, and T is the total torque generated by each pulse (for the 12 jets listed, $T = 4.74238 \times 10^{*5}$ nt-m).

Since the model was linear, the result of linearly varying the pulse was a straight line. Table 3 gives each value of pulse length with the maximum compressive member load that was produced. Figure 5 shows the same results plotted.

In each of these cases, the maximum load was produced in a longeron at the base of the truss. The question, then, is which of these pulse lengths produced a longeron load that exceeded the buckling load? Figure 5 shows a line at a load value of 7562 nt (1700 lbf) which represents the approximate Euler buckling load for a 5 meter longeron. Clearly, only the 80 ms pulse produced a load below this value. Thus, to fire a single pulse of the PROS jets without causing a truss member to fail, it would be necessary to have a pulse length of approximately 80 ms or reduce the total torque of the jets to less than that used here. The next section investigates that possibility.

Before proceeding, however, it is important to note the amount of actual motion of the orbiter and SAVE structure that was produced by the 12 jets fired in this section. In the case where the jets were fired in a single 80 ms pulse, the center of mass of the orbiter moved at an approximate rotational rate (pitch) of only 0.1 degrees/sec while a 150 ms pulse produced an approximate rate of only 0.2 degrees/sec. The peak acceleration produced in each case was higher than would normally be used in a maneuver, but because the duration of the pulse was so much shorter than the natural frequency of the system, the input was essentially an impulsive torque. Thus, the system vibrated at its natural frequency with an amplitude determined by the length of the pulse and, despite the relatively low angular rates, the oscillations of the system produced member loads which would jeopardize the structure. Obviously, if large motions of the orbiter are required at a time when a large structure such as the SAVE truss or a space station truss section is attached, it will be necessary to significantly limit the amplitude of the oscillations to avoid having to jettison the structure.

Figure 4 - One Pulse Forcing Function



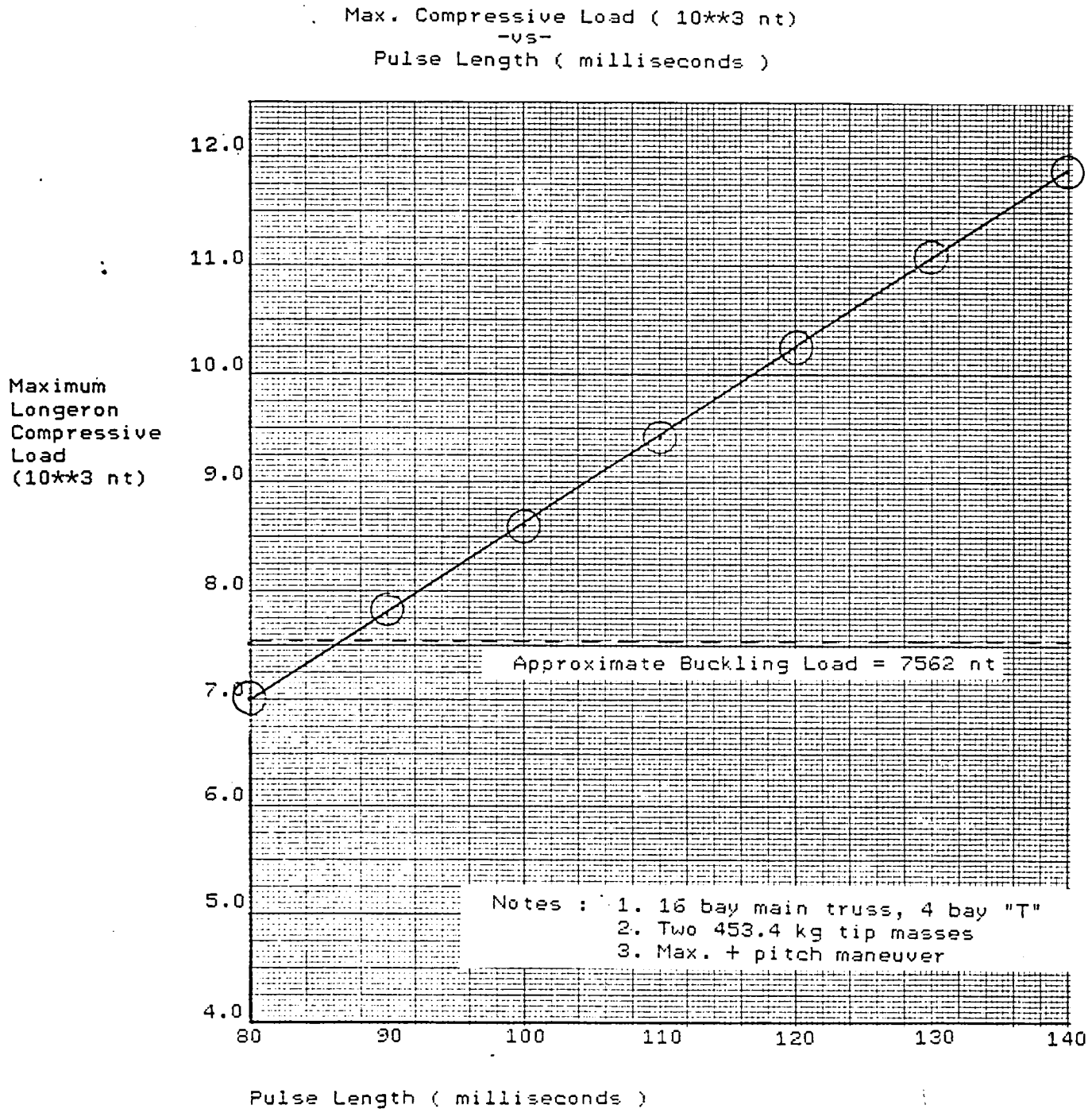
T = Total torque produced by given set of PRCS jets

L = Length of pulse

TABLE 3 - Maximum Compressive Member Loads produced by
a given Pulse Length

| Pulse Length (milliseconds) | Maximum Compressive Load in Truss Member (nt) |
|--------------------------------|--|
| 80 | $6.9279 \times 10^{*3}$ |
| 90 | $7.8200 \times 10^{*3}$ |
| 100 | $8.6280 \times 10^{*3}$ |
| 110 | $9.4363 \times 10^{*3}$ |
| 120 | $1.0253 \times 10^{*4}$ |
| 130 | $1.1065 \times 10^{*4}$ |
| 140 | $1.1860 \times 10^{*4}$ |
| 150 | $1.2668 \times 10^{*4}$ |

Figure 5



6.2 Longeron Load -vs- Torque Produced

In this part of the analysis the number and location of PRCS jets that were fired was varied to produce a range of input pitch torques. The aim here was to determine the amount of torque that could be tolerated with a single 80 ms pulse, without causing a failure of a truss member.

Table 4 shows the jets that were fired in each case, with the torque produced, and the corresponding maximum compressive member load. Figure 6 shows the results plotted as load versus torque.

The result here is a generally straight line, although it should be noted that when these cases were set up, the roll and yaw torques were allowed to be slightly different. For example, case #2 was set up by "turning off" four of the jets that were fired in case #1. An effort was made to eliminate jets which produced opposite reactions, but it was not possible to assure that the net roll and yaw torques remained the same from one case to another. The result of this was a slight change in the roll and pitch motions from case to case, and hence a slight difference in the pitch plane reaction.

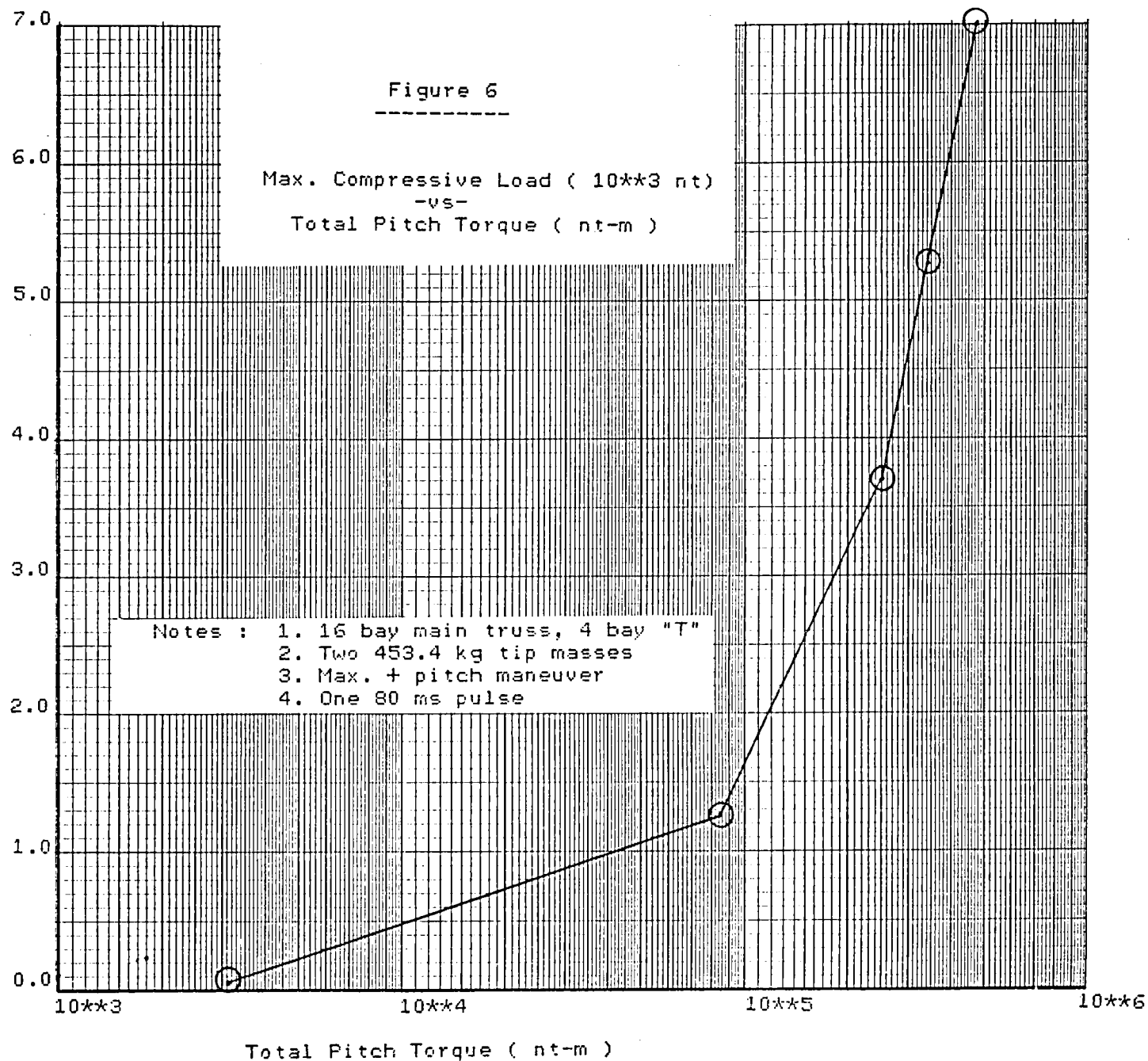
When the issue of truss member buckling is considered, it is clear from figure 6 that by reducing the input torque, it is likely that a safe load level can be maintained. From these results, and those from the previous section, a few simple interpolations can be performed to determine a combination of pulse length and input torque that will maintain an acceptable member load level.

Table 4 - Maximum Compressive Load produced by smaller sets of RCS jets

| Case # | Jet Identifiers | Total Pitch Torque (nt-m) | Max. Compressive Load (nt) |
|--------|--|--------------------------------|---------------------------------|
| 1 | F1D R1U L1U F5R F2D R2U L2U F5L F3D R4U L4U F4D | $4.74338 \times 10^{**5}$ | $6.92790 \times 10^{**3}$ |
| 2 | F3D R1U L1U F4D R2U L2U R4U L4U | $3.39874 \times 10^{**5}$ | $5.27024 \times 10^{**3}$ |
| 3 | R1U L1U R2U L2U R4U L4U | $2.50614 \times 10^{**5}$ | $3.69267 \times 10^{**3}$ |
| 4 | L4U F5R R4U F5L | $8.40777 \times 10^{**4}$ | $1.24778 \times 10^{**3}$ |
| 5 | F5R F5L | $3.09560 \times 10^{**3}$ | $4.46930 \times 10^{**3}$ |

Maximum
Longeron
Compressive
Load
(10×3 nt)

17



6.3 Member Load -vs- Pulse Frequency

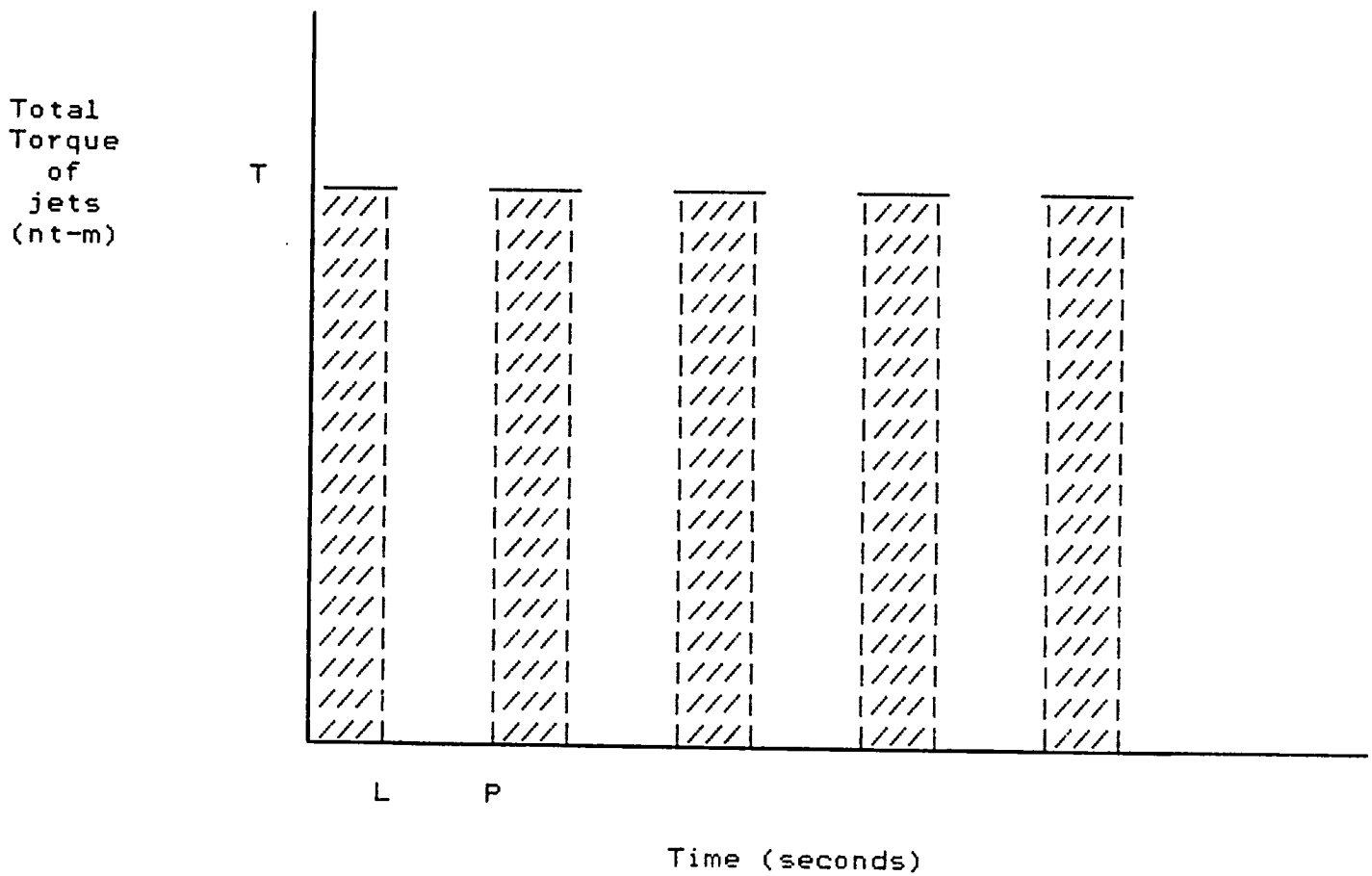
The purpose of this section of the study was to show, in a simple manner, the variation of response with the frequency at which the RCS jets were fired. The procedure was to evaluate four cases, in which five 80 ms pulses of the 12 RCS jets listed in section 5.0 were fired at various frequencies. Figure 7 shows this forcing function, where L is 80 ms, T is 4.74338×10^{-5} nt-m (as before), and P is varied with each case. In each case, the maximum compressive load that was produced in a truss member after each pulse was determined.

The choice of frequencies was based on the value of the fundamental frequency of the SAVE structure. The first mode of the SAVE structure is bending about the y-axis (pitch), with a corresponding natural frequency of 0.5588 Hz. The frequencies that were used for the four RCS firings were one half, four thirds, and twice the natural frequency as well as the natural frequency itself. Table 5 shows the load produced after each pulse for each of the four frequency values, and figure 8 shows the same results plotted.

As expected, when the pulses occurred at the natural frequency, the response built up because every oscillation of the structure was accentuated by a pulse of the RCS jets. At half the natural frequency, every other oscillation was accentuated by a pulse, but the response was less than before, since the amplitude of each non-accentuated oscillation was reduced by damping. Conversely, in the cases where the frequency was $4/3$ and twice the natural frequency, various oscillations of the structure were cancelled by the pulses of the RCS jets and the member loads were correspondingly small.

In each case, except where the pulse frequency was twice the natural frequency, only two pulses were required to exceed the buckling load. It seems, then, that any closely spaced pulses, regardless of their frequency, have the potential to jeopardize the structure. Of course, the number of RCS jets could be reduced as before to lessen the danger of member failure.

Figure 7 - Five Pulse Forcing Function



T = Total torque produced by given set of PRCS jets

L = Length of pulse

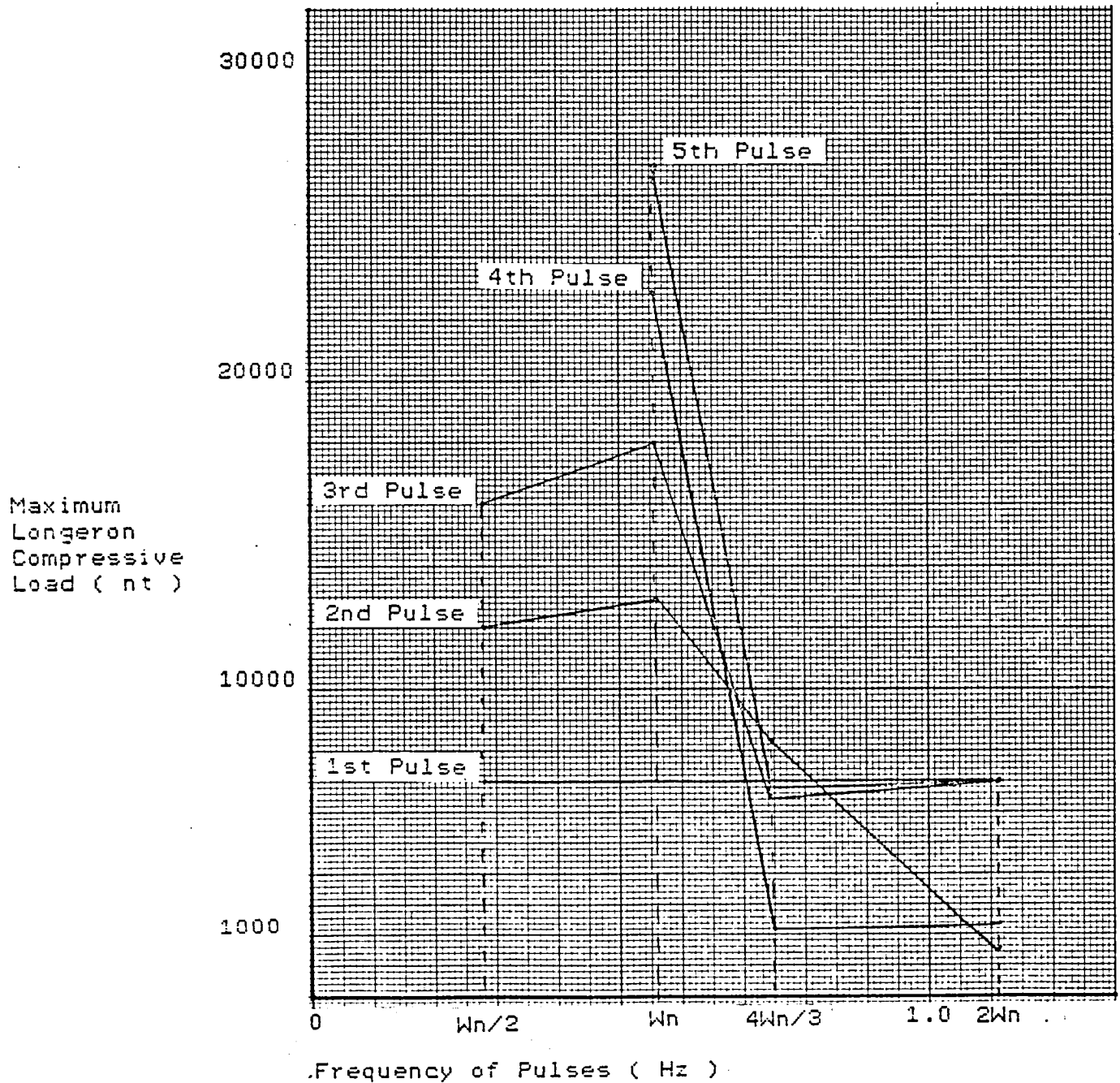
P = Period of pulses ($P = 1/\text{freq.}$)

Table 5 - Maximum Compressive Load produced by varying the frequency of RCS jet pulses.

| Pulse | Maximum Compressive Load (nt) | | | |
|-------|--------------------------------------|----------------------------------|--------------------------------------|--|
| | 1/2 Natural Frequency (0.2794 Hz) | Natural Frequency (0.5588 Hz) | 4/3 Natural Frequency (0.7451 Hz) | Twice Natural Frequency (1.1176 Hz) |
| 1 | $6.928 \times 10^{*3}$ | $6.928 \times 10^{*3}$ | $6.928 \times 10^{*3}$ | $6.928 \times 10^{*3}$ |
| 2 | $1.204 \times 10^{*4}$ | $1.285 \times 10^{*4}$ | $8.374 \times 10^{*3}$ | $1.040 \times 10^{*3}$ |
| 3 | $1.612 \times 10^{*4}$ | $1.792 \times 10^{*4}$ | $6.502 \times 10^{*3}$ | $7.043 \times 10^{*3}$ |
| 4 | ----- | $2.271 \times 10^{*4}$ | $2.095 \times 10^{*3}$ | $2.035 \times 10^{*3}$ |
| 5 | ----- | $2.680 \times 10^{*4}$ | $6.785 \times 10^{*3}$ | $6.988 \times 10^{*3}$ |

Figure 8

Max. Compressive Load (nt)
-vs-
Frequency of Pulses (Hz)



- Notes :
1. 16 bay main truss, 4 bay "T"
 2. Two 453.4 kg tip masses
 3. Max. + pitch maneuver
 4. One 80 ms pulse
 5. W_n = natural freq. = 0.5584 Hz

7.0 CONCLUSIONS

The results presented in the preceding sections indicate that it is possible to define a scenario for firing the orbiter Primary Reaction Control System (PRCS) jets which will not jeopardize the structural integrity of an attached structure. In the particular case that was investigated by this study, it is clear that the SAVE structure would be able to withstand a moderate amount of shuttle maneuvering if care was taken to determine precise operational constraints. However, since the scope of this study was sufficient only to establish a broad outline of allowable orbiter motions, more precise definition must be obtained. In particular, it would be highly desirable to include a flexible model of the orbiter as well as a more realistic set of PRCS firing patterns and, of course, to begin a similar investigation with actual space station truss sections.

8.0 REFERENCES

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Standard Bibliographic Page

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|---|--|---|--|---|--|
| 1. Report No. NASA TM-89031 | | 2. Government Accession No. | | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Analysis of the Effects of Firing Orbiter Primary Reaction Control System Jets with an Attached Truss Structure | | | | 5. Report Date August 1986 | |
| | | | | 6. Performing Organization Code 483-31-03-01 | |
| 7. Author(s) M. Kaszubowski and J. P. Raney | | | | 8. Performing Organization Report No. | |
| 9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665 | | | | 10. Work Unit No. | |
| | | | | 11. Contract or Grant No. | |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546 | | | | 13. Type of Report and Period Covered Technical Memorandum | |
| | | | | 14. Sponsoring Agency Code | |
| 15. Supplementary Notes M. Kaszubowski: PRC Kentron, Inc., Hampton, Virginia. J. P. Raney: Langley Research Center, Hampton, Virginia. | | | | | |
| 16. Abstract A study was conducted to determine the dynamic effects of firing the orbiter primary reaction control jets during assembly of protoflight Space Station structure. Maximum longeron compressive load was calculated as a function of jet pulse time length, number of jet pulses, and total torque imposed by the reaction control jets. The study shows that it is possible to fire selected jets to achieve a pitch maneuver without causing failure of the attached structure. | | | | | |
| 17. Key Words (Suggested by Authors(s)) Space Station, Space Construction, Orbiter Reaction Control System, Structural Loads, Structural Failure | | | | 18. Distribution Statement Unclassified - Unlimited Subject Category 18 | |
| 19. Security Classif.(of this report) Unclassified | | 20. Security Classif.(of this page) Unclassified | | 21. No. of Pages 23 | |
| | | | | 22. Price A02 | |

For sale by the National Technical Information Service, Springfield, Virginia 22161

